

NASA Battery Workshop 2003



Update on Development of 360V, 28 kWh Lithium Ion Battery

Francis Davies NASA-JSC Battery Group Houston fdavies@ems.jsc.nasa.gov

Eric Darcy NASA-JSC Battery Group Houston edarcy@ems.jsc.nasa.gov

Phil Cowles COM DEV Battery Group Cambridge Ontario philip.cowles@comdev.ca

Brad Irlbeck NASA-JSC EAPU Project Engineer Houston birlbeck@ems.jsc.nasa.gov

John Weintritt NASA-JSC Battery Group Houston jweintri@ems.jsc.nasa.gov

Abstract

Engineering unit submodule batteries (EUSB) the 360V, 28kWh EAPU battery were designed and assembled by COM DEV. These submodules consist of Sony Li-Ion 18650HC cells in a 5P-41S array yielding 180V, 1.4 kWh. Tests of these and of substrings and single cells at COM DEV and at JSC under various performance and abuse conditions demonstrated that performance requirements can be met. The thermal vacuum tests demonstrated that the worst case hot condition is the design driver. Deficiencies in the initial diode protection scheme of the battery were identified as a result of test failures. Potential solutions to the scheme are under development and will be presented.

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- Description of design
- Design meets performance requirements
- Activation of cell PTC current limiting switch while hot is design driver
- PTC current limiting switches fail under high voltage short conditions
- Diode scheme fixes problem: battery can recover after a hard short
- Battery modules are fail-safe to a smart short
- Initial diode scheme is not two-failure tolerant, resulting in fire
- Collateral damage test is a success
- Conclusions and Future Work

10 EUS Batteries Built for Engineering Tests at JSC and Com Dev



01

- Acceptance Test
- Mission Cycling (30 charge / discharge cycles)

02

- Spare

03

- Acceptance Test
- Mission Hot Thermal Vac
- *Thermal Cycling*
- *Short Circuit*
- *Overcharge*

04

- Acceptance Test
- Mission Cold Thermal Vac
- Short Circuit

05

- Acceptance Test
- Mission Hot
- Short Circuit

06

- Acceptance Test
- Collateral Damage

07

08

- Acceptance Test
- Mission Hot Thermal Vac with Helium
- Collateral Damage

09

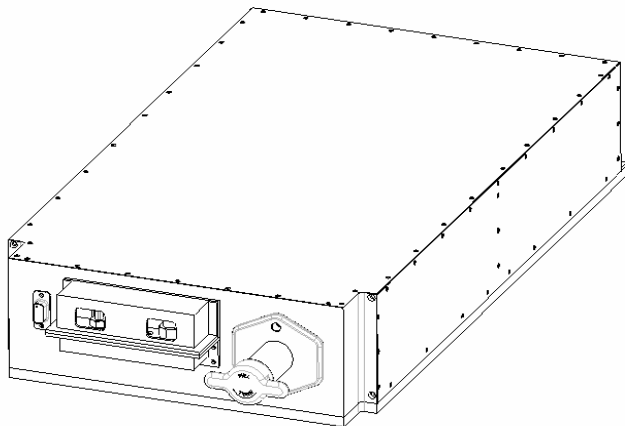
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- *Short Circuit*
- *Smart Short*

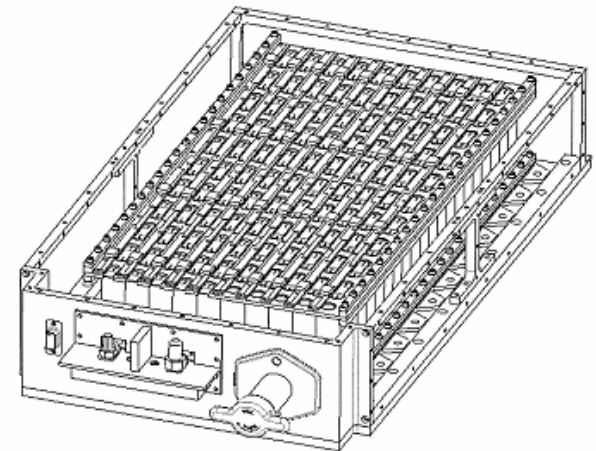
Description of EUS design



- EUS (engineering Unit Substring) is 41S 5P, represents 1/35 of 82S 88P flight battery.
- Cell mounting and tray configuration are same as flight design.



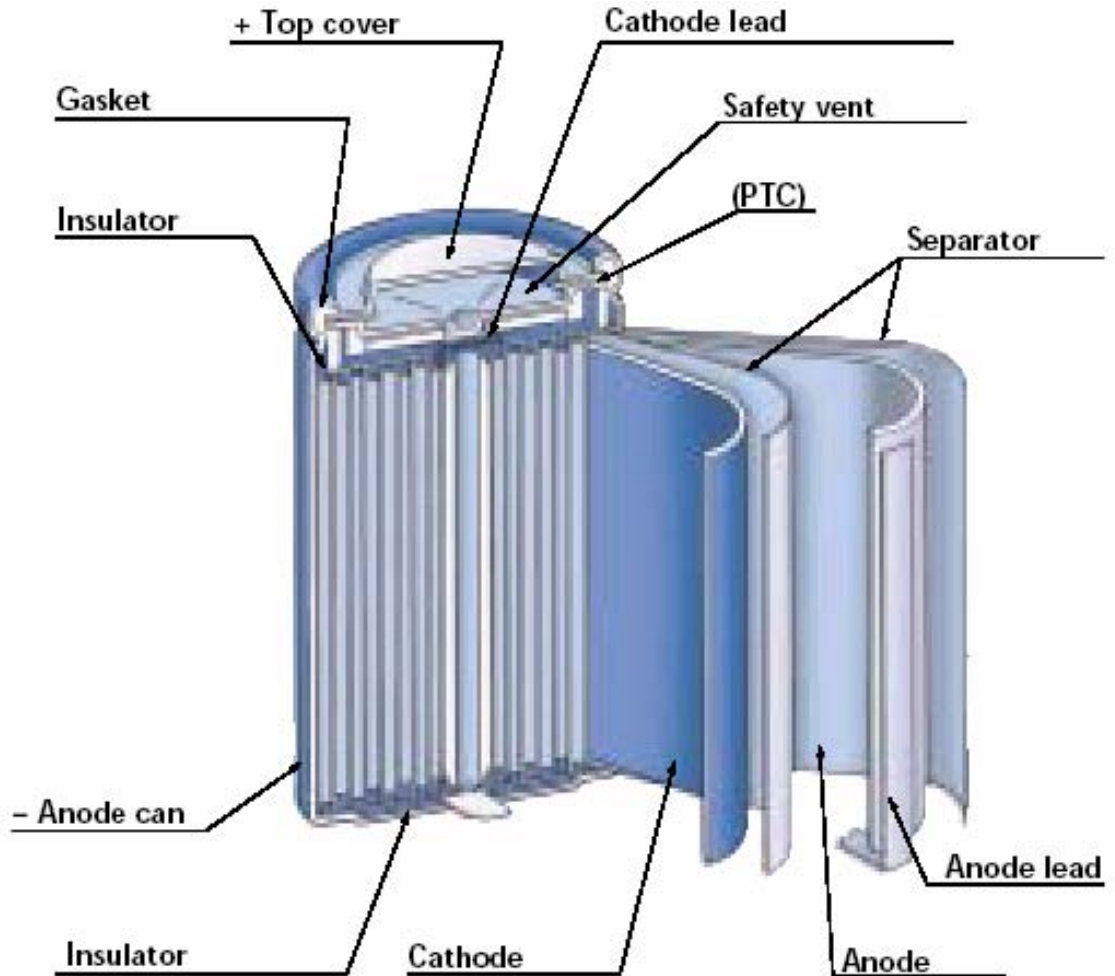
- **Electrical Config of 41S-5P**
- **180 V Charge (4.4 V / cell)**
- **Diodes Across Groups of 6 Cells to Allow PTC Performance for Short Circuit Protection**
- **Also Includes Heaters, Temp Sensors, Deadface Switch, and Interfaces**



Description of design



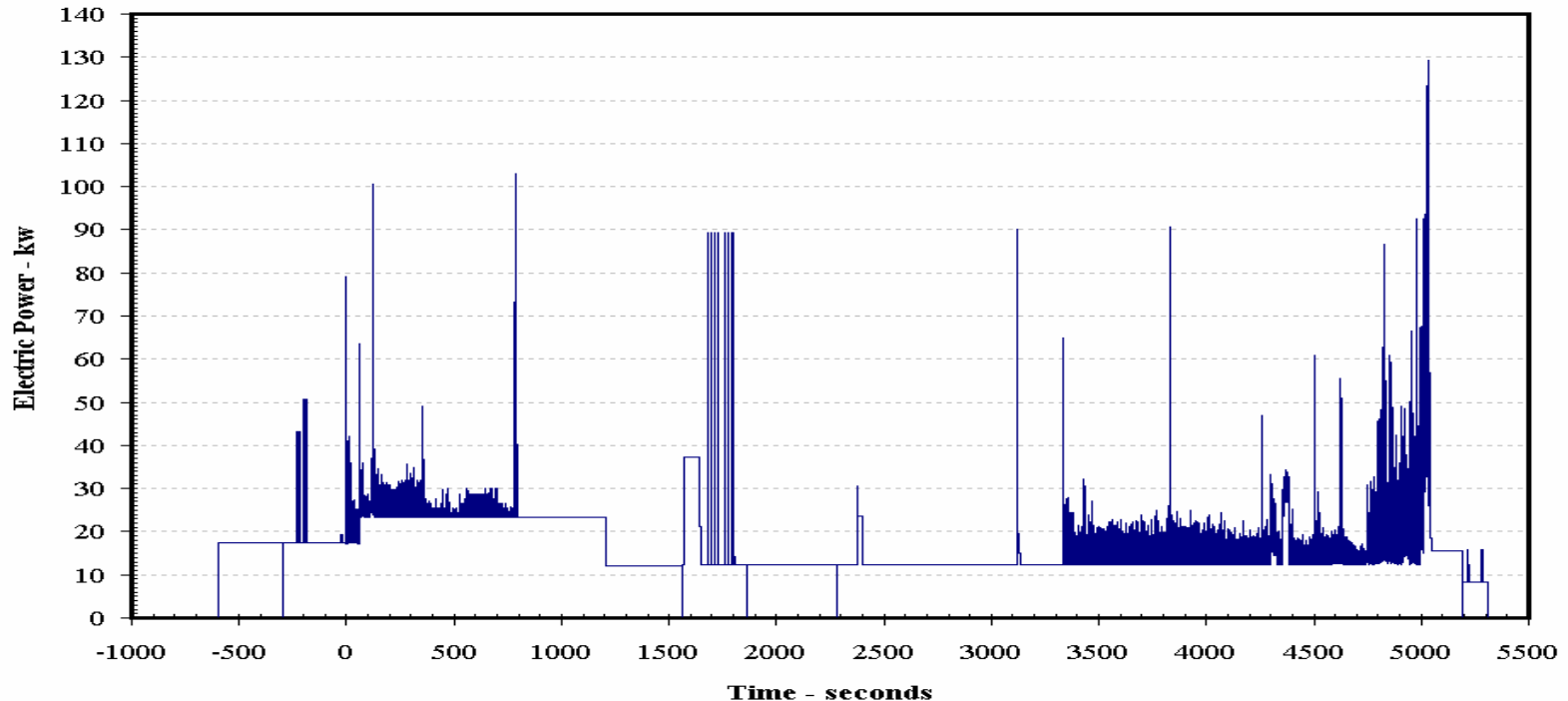
- Sony Hard Carbon 18650 Li-Ion Cell
- Mature technology - in mass production since 1992
- Production standard frozen since 1995
- Good high power and lifetime characteristics
- 5.4Wh @ 40.5g
=>133Wh/kg when charged to 4.2V
- Highly uniform production
- Tested by many organizations



Power profile requires 130 kW, 3s pulse near end



EAPU Electric Power - 2 APU, 70 gpm Case

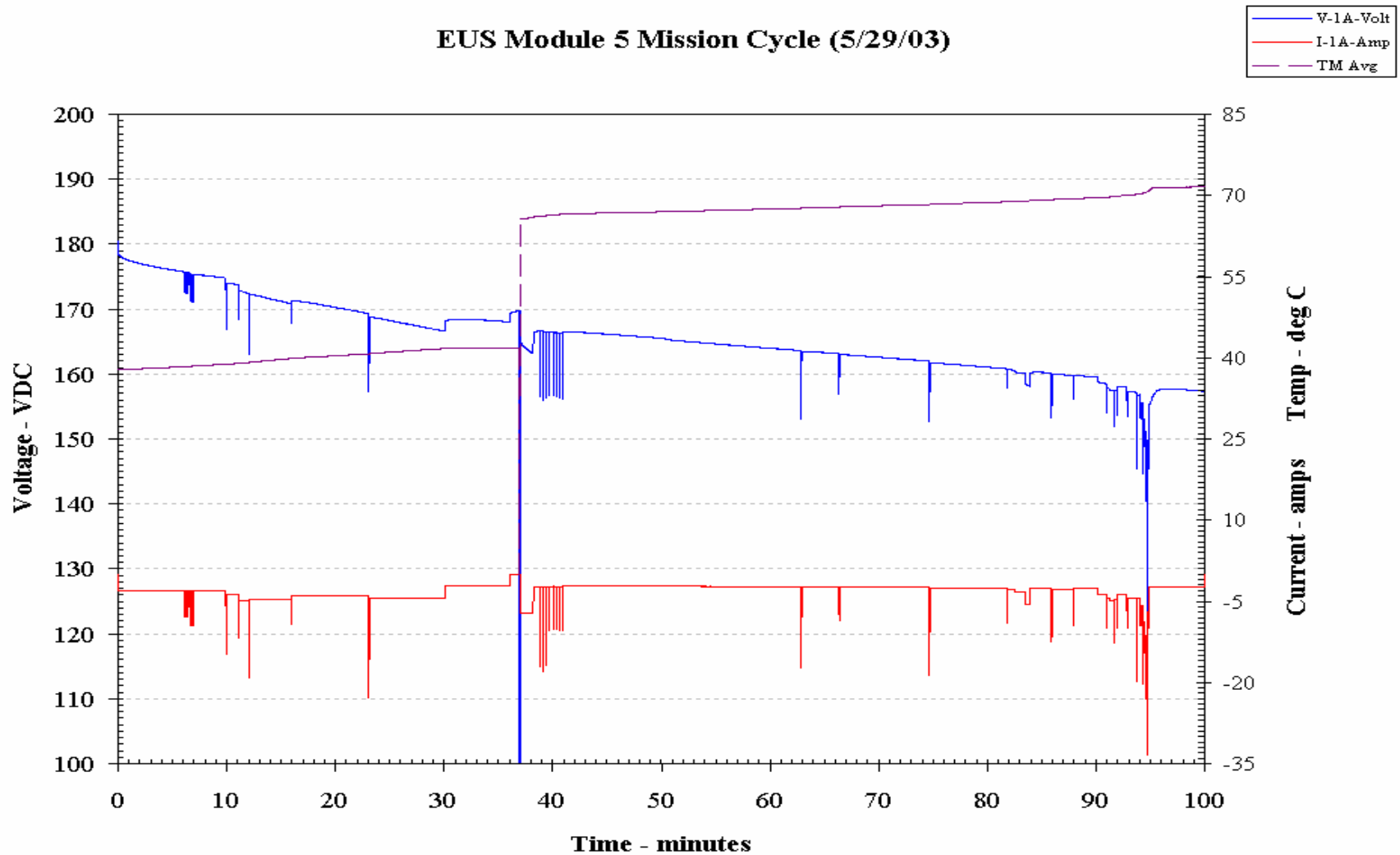


Mission Time:	99 minutes (36 ascent, 63 descent)
Voltage	230 to 360 VDC
Power / Energy	28 kw-hr and 130 kW for 3 sec
Life:	3 years & 6 missions (30 charge/discharge cycles)
Temperature Environment:	-90 C to 80 C

Mission Discharge Showed Excellent Performance



EUS Module 5 Mission Cycle (5/29/03)

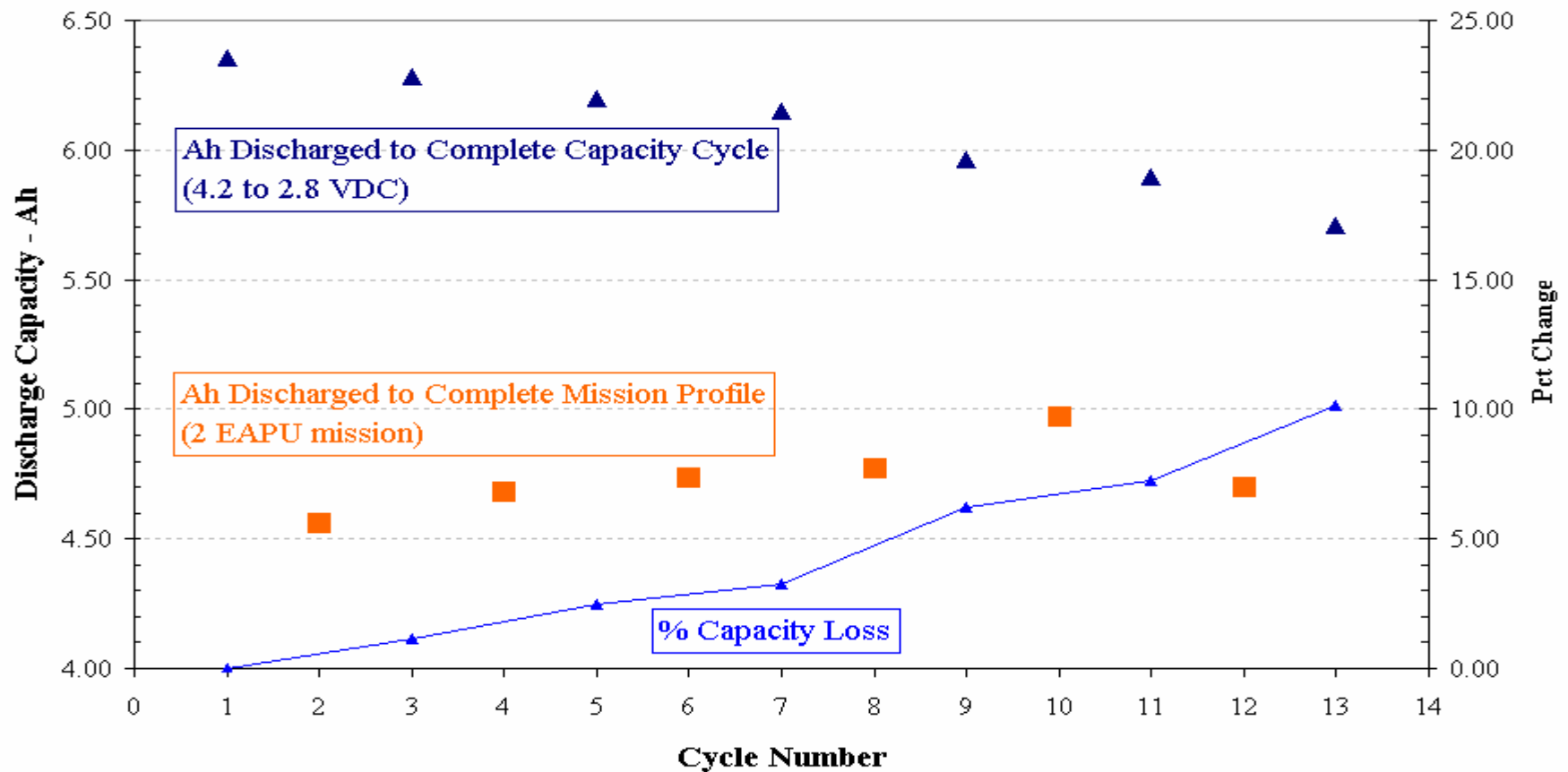


Cycle Life Adequate



S/N 03 Capacity with Cycles

(7 capacity cycles at ambient temp, 6 mission cycles at -5 to 65 C)



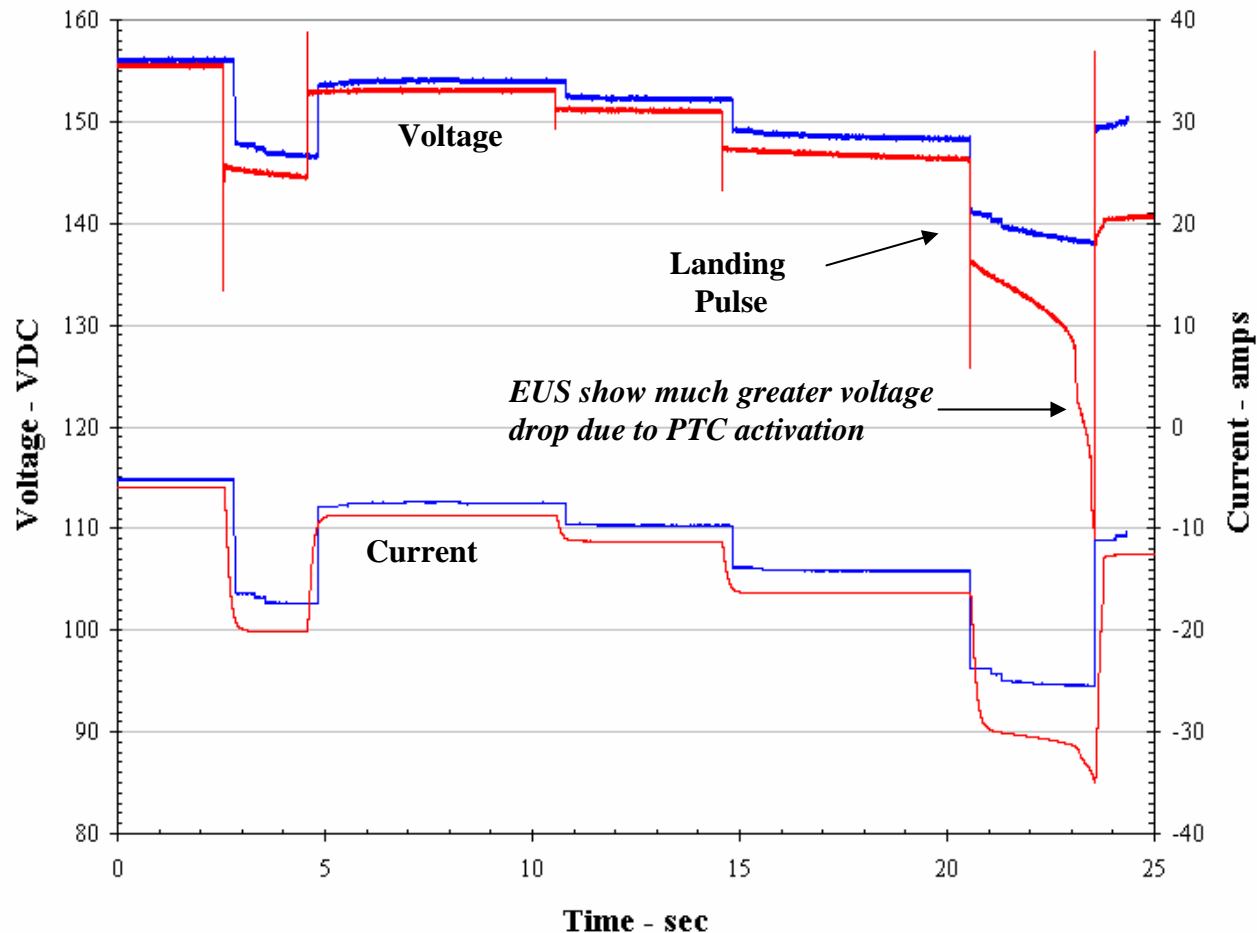
PTC activation limits performance



EUS and Prototype Module Comparison - Hot Mission Landing Pulse

Prototype - 92 P Profile

EUS - 80 P Profile

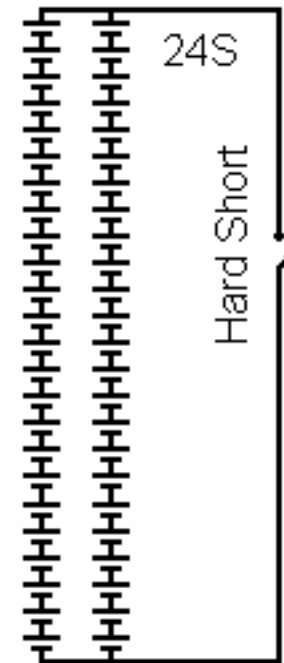
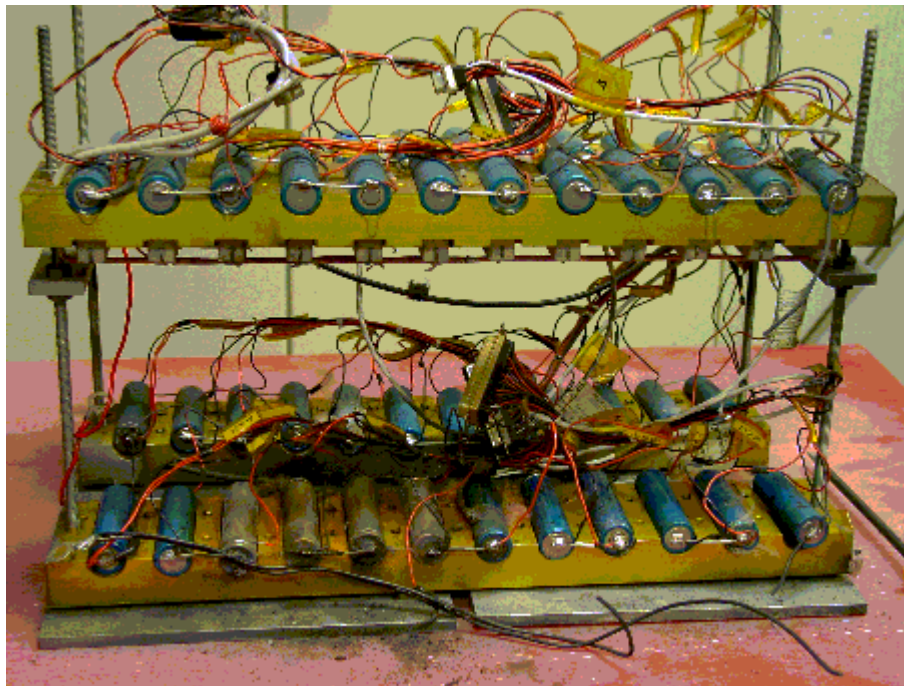


- **EUS Sized for the Cold Case (voltage drop)**
- **Results Show the Hot Case is the Sizing Driver with the Sony Cells (PTC trip)**
- **Additional Parallel Strings Are Needed with the Sony Cells**
- **Other 18650 Cells Show Better Results**

Initial 24S Short-Circuit Test



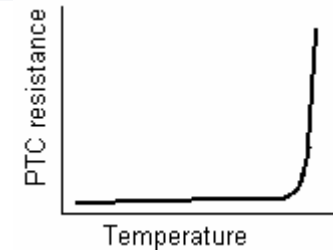
- Initial design review raised doubts that PTC could handle the high voltages that result when PTCs activate during short circuits.
 - Multiple PTCs in series: only one will trip and take all the voltage.
- Short circuit on 24S x 2P unit showed cell overheating and venting (shown below)
- Measurements showed cells momentarily experiencing large negative voltages.



Protective devices in COTS cells: PTC



- The PTC is a Positive Temperature Coefficient device. Its resistance jumps dramatically when current heats it above the threshold temperature
- PTCs act differently after first trip: higher cold resistance, shorter trip time, higher withstand voltage.



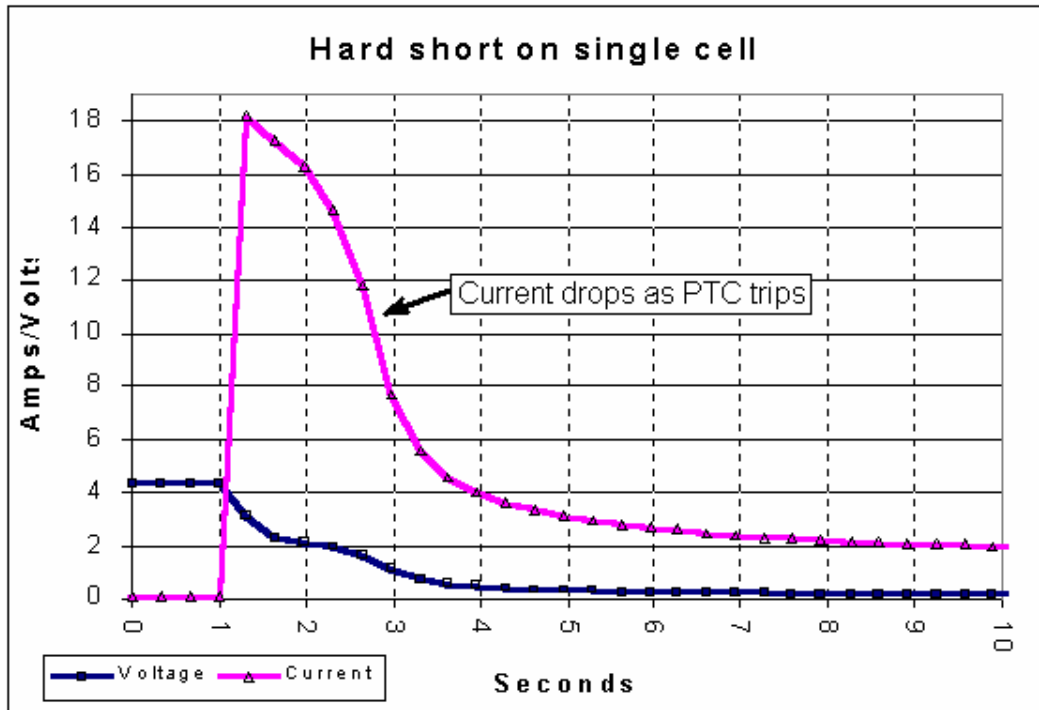
Notes:

PTC current tapers to approx 1.1 A after approx. 200 sec.

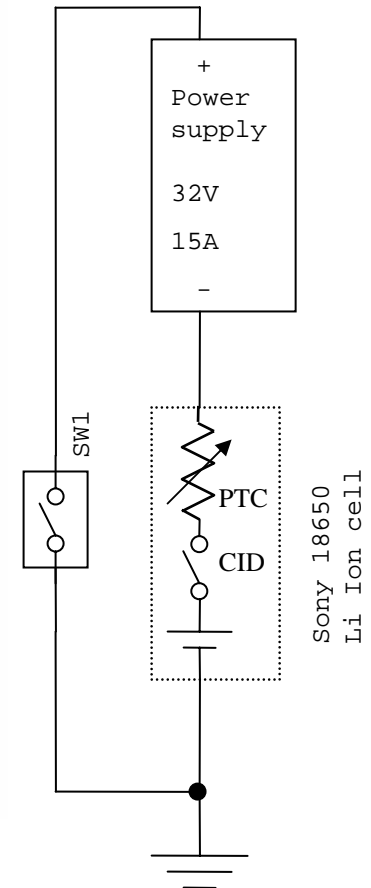
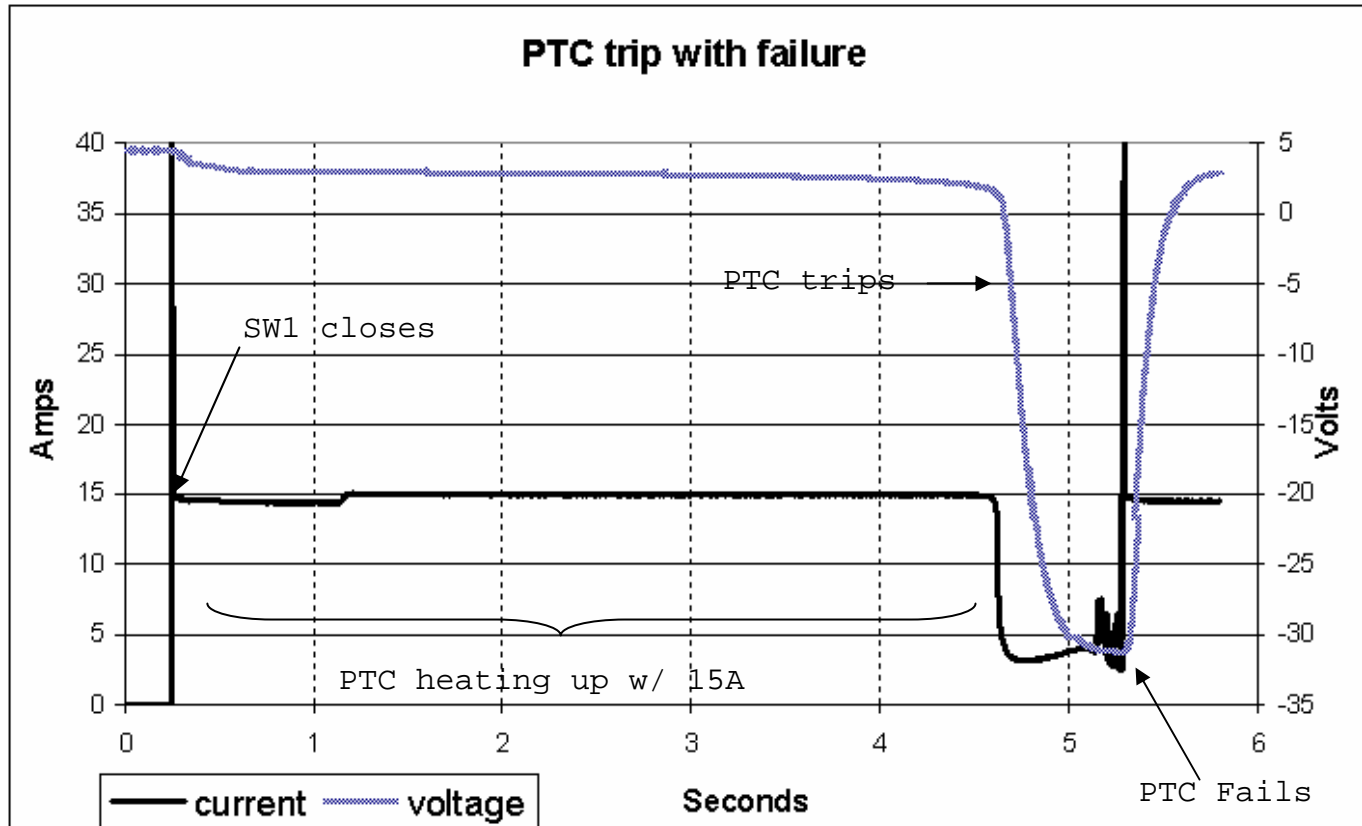
After trip, voltage across cell is low ($<0.1V$) but most of the voltage drop is across PTC.

After trip, temperature of case at PTC end of cell reached approx 170F (76C). Large thermal gradient along length of cell case (22F, 12C)

Tests at different voltages show PTC holds constant power (4-5W) over wide voltage range (4V to 34V)

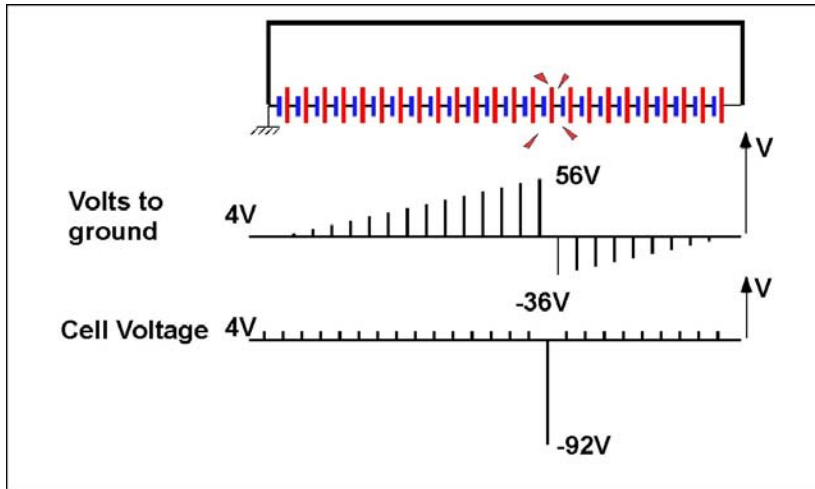


PTCs fail under high voltage short conditions



- Power supply simulates large battery (approx 8 cells).
- PTC trips after ~4.6 seconds, then fails short after ~5.3 sec.

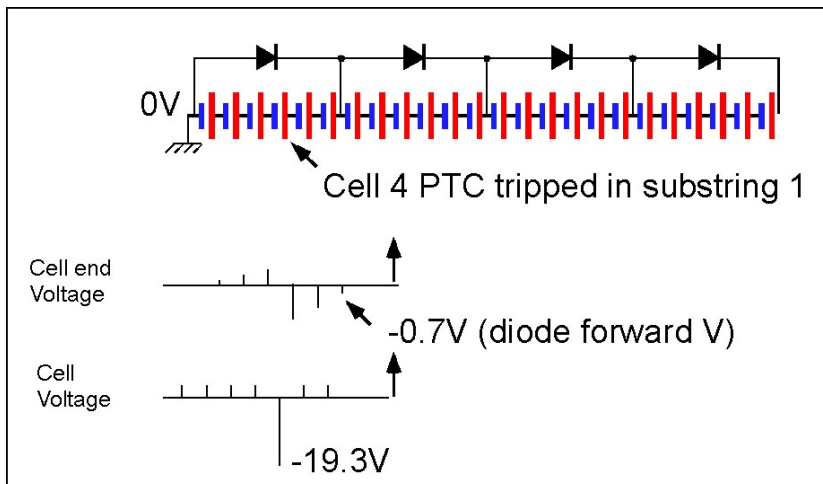
Description of diode scheme: Details



1 One cell fails with high reverse voltage

Notes:

1. Diagram has reduced number of cells for simplicity
2. If the short is removed, then no current will flow through the PTCs, and they will cool down, resetting themselves to a low impedance state.
3. Diodes allow PTCs to share the voltage, thus reducing voltage stresses on PTCs.
4. Scheme only works for discharge current, not charge current.

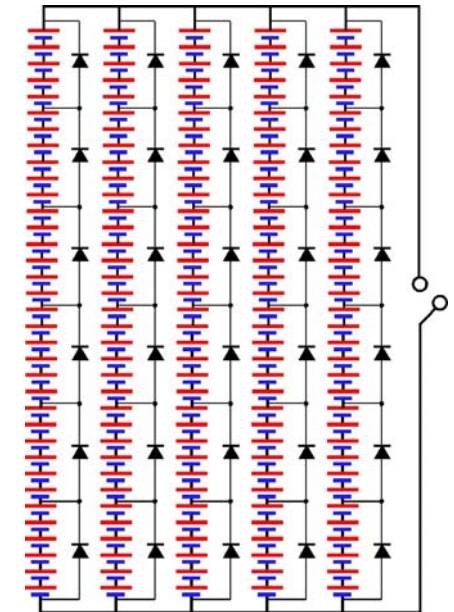
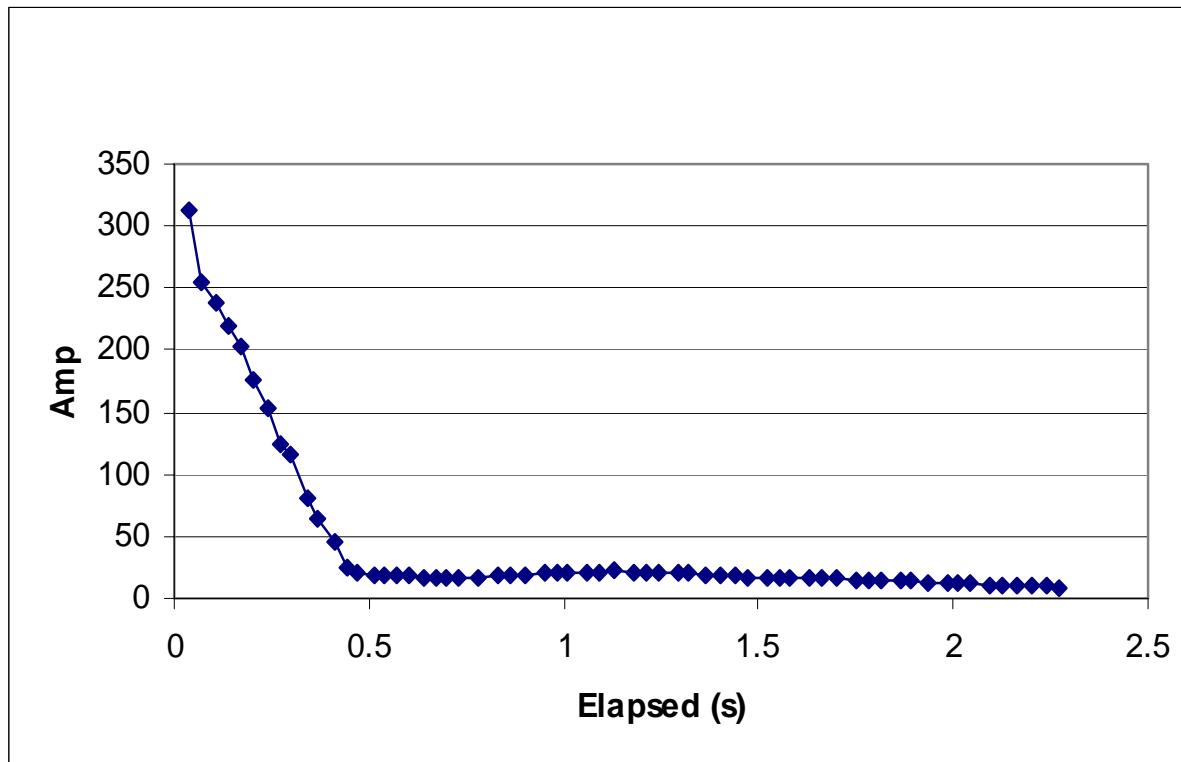


2 Diodes limit reverse voltage – no damage

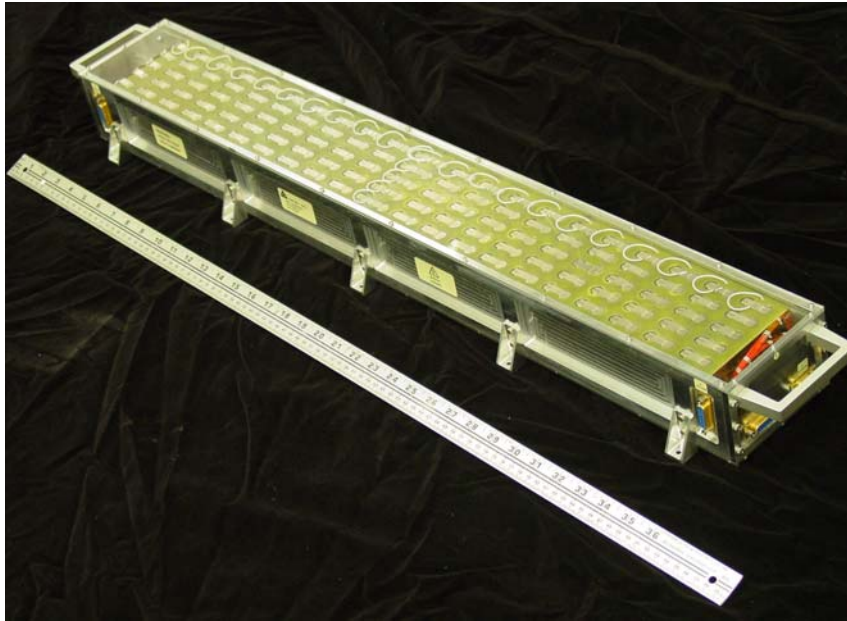
Hard short circuit testing successful



- Result of short circuit on 41S 5p battery with diodes
-- no damage to cells or performance.



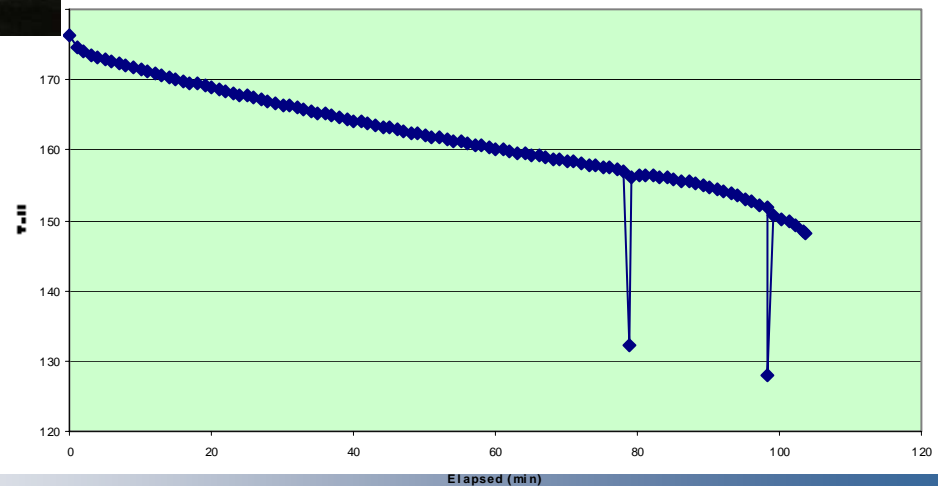
Diodes allow module to recover from a hard short



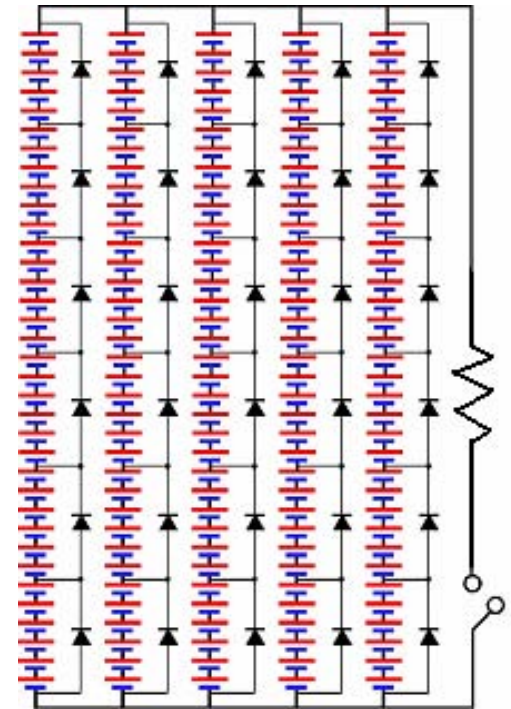
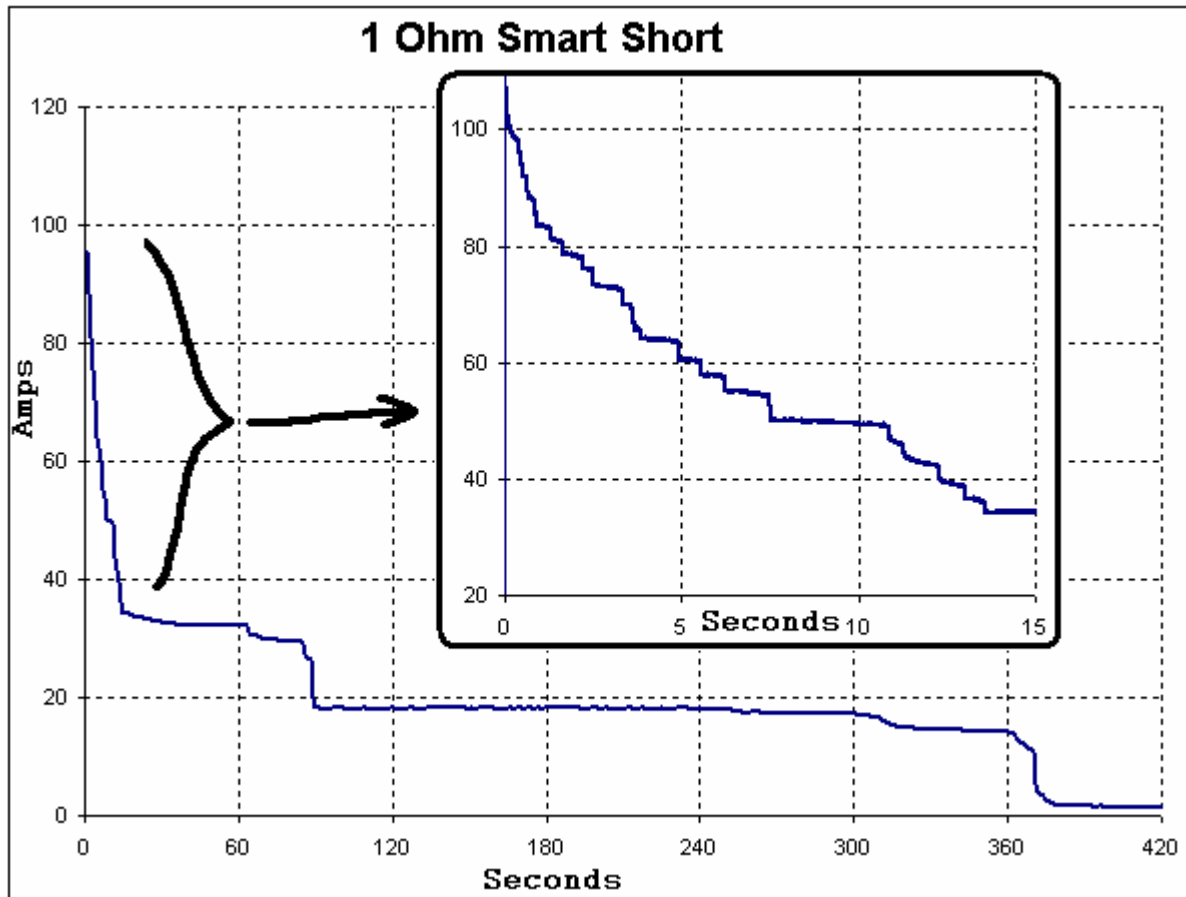
Proof is in the testing

41S-5P submodule with
1 bypass diode for each 6
cells in series tolerates short
and discharges nominally
after recharging

SubM 01 Mission Post Short



Smart short showed safe shutdown

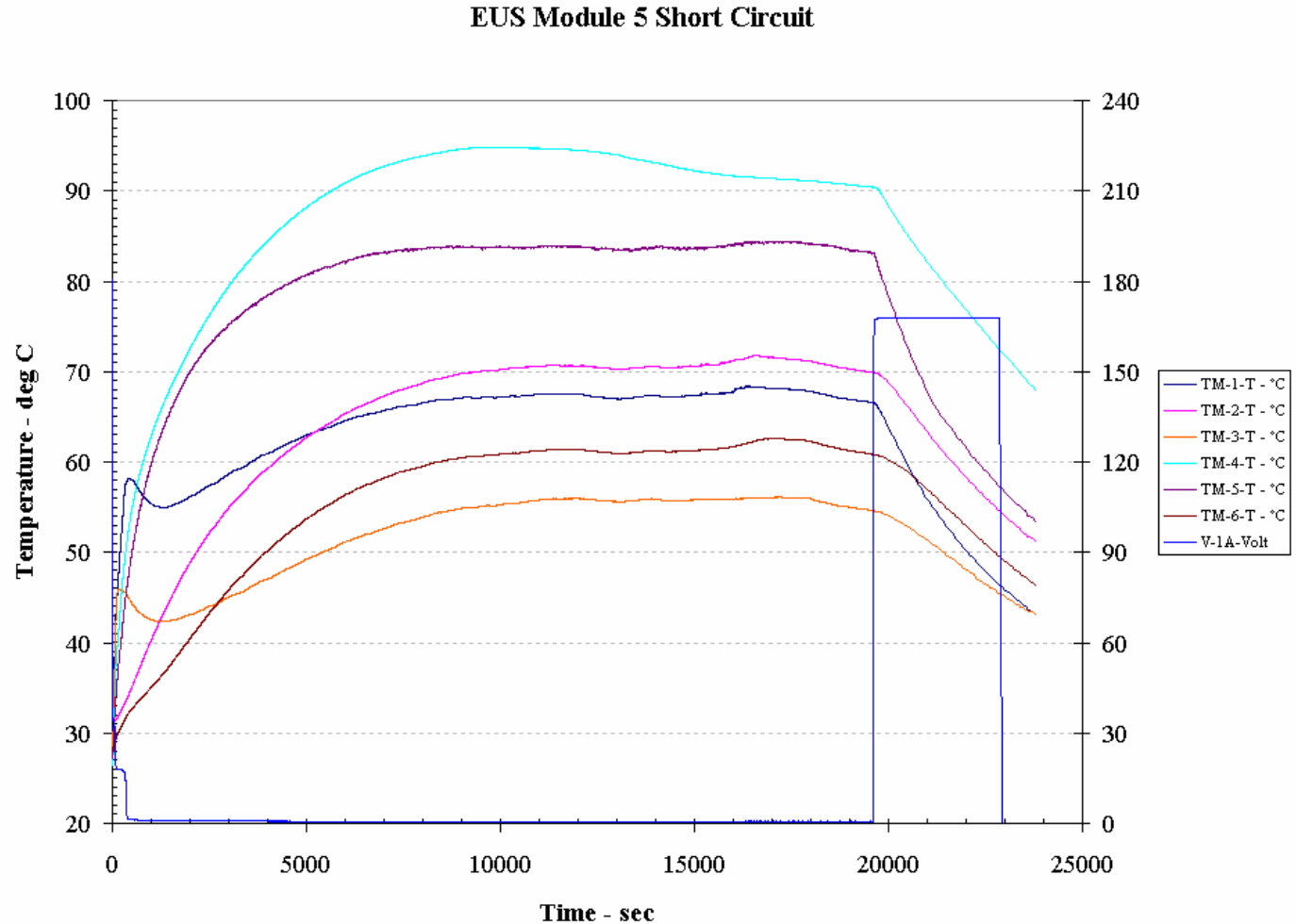


- Smart short with 1 ohm: PTCs

Smart short showed fail-safe operation.



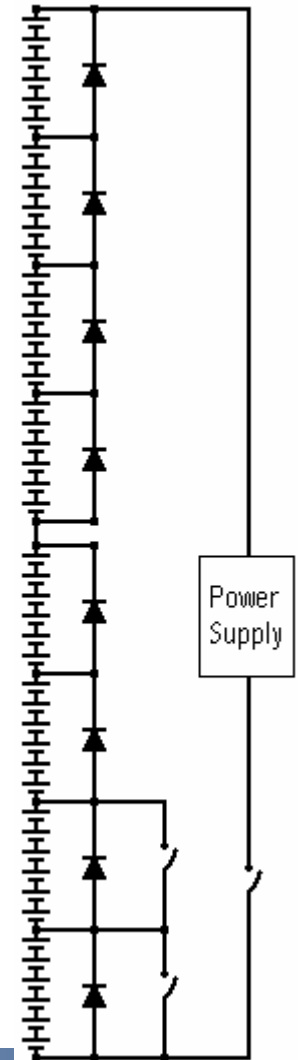
- External current dropped below 0.5A after 2.5 hrs
- Internal temperature kept rising due to self heating of PTCs.
- No physical damage to battery.
- Difference in PTC trip times led to imbalance in state-of-charge between cells in battery.



Initial diode scheme is not two-failure tolerant.



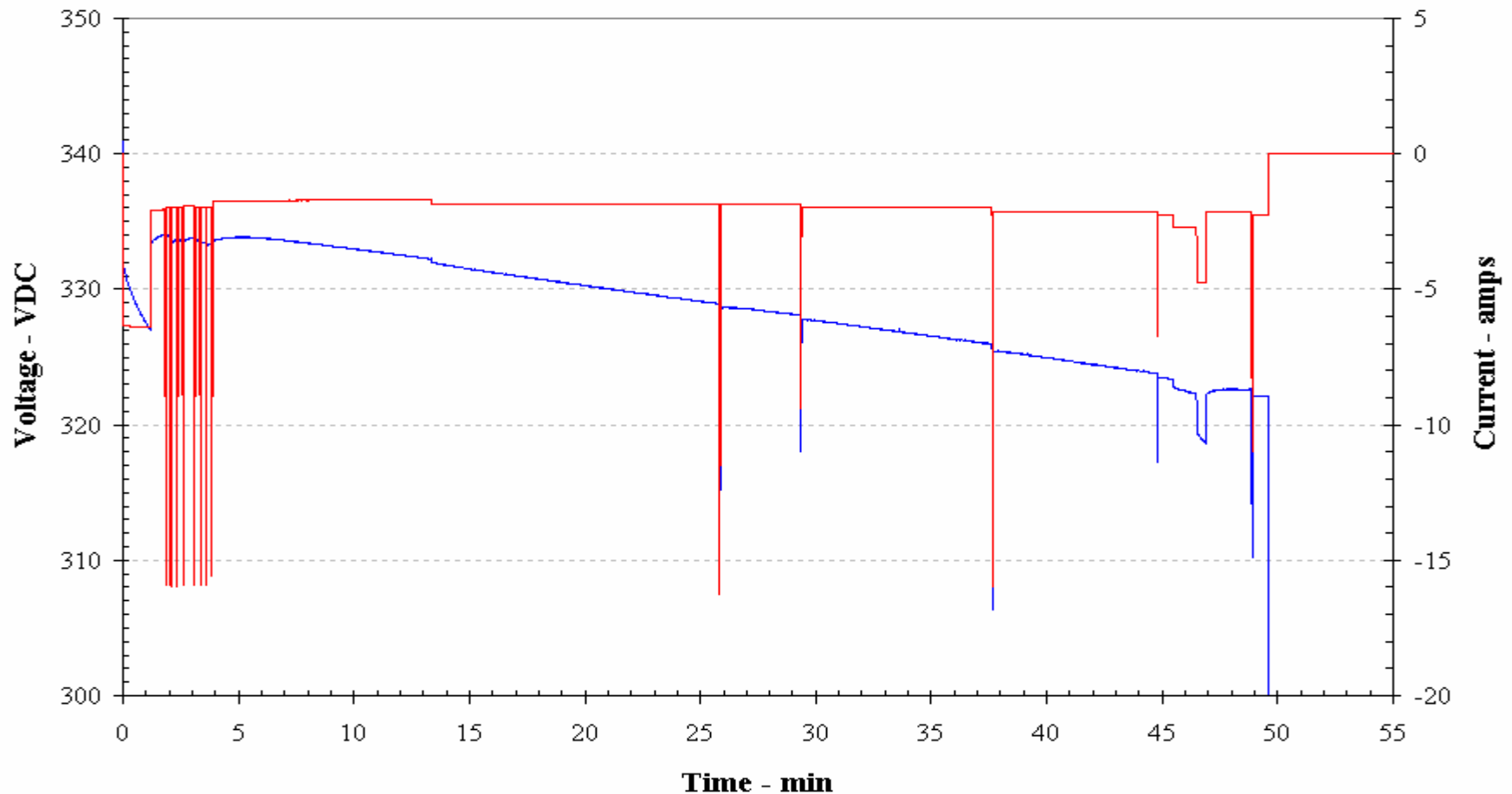
- Test simulated two diodes failing short by closing relays in parallel with diodes.
- Fire caused by cells venting due a combination of PTC heating and overcharge.



Thermal Vac test showed corona failure.



EUS Module 7,8 - Short Mission Cycle Descent 8-18-03



Thermal Vac test showed corona failure.

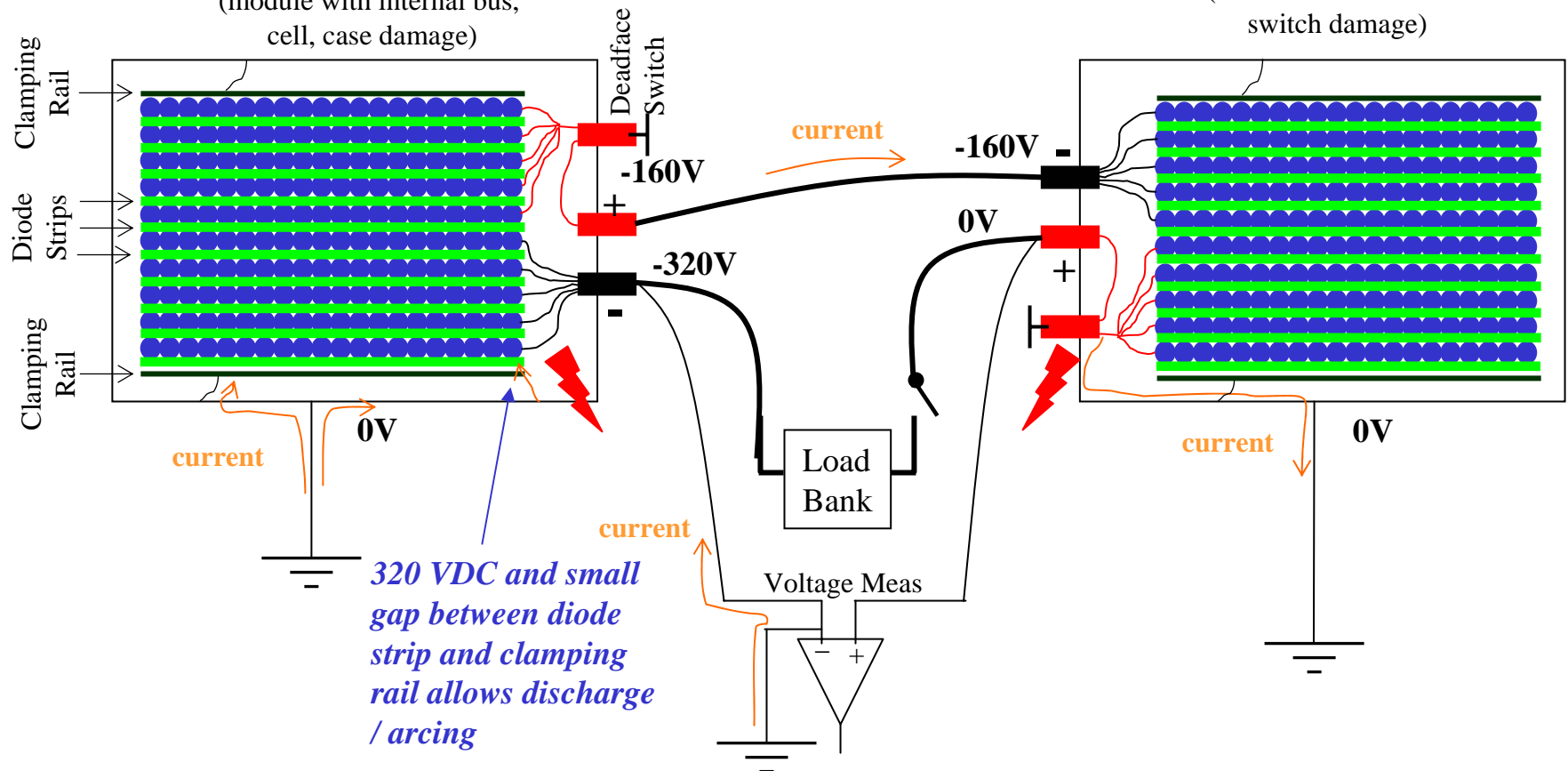


EUS 7

(module with internal bus, cell, case damage)

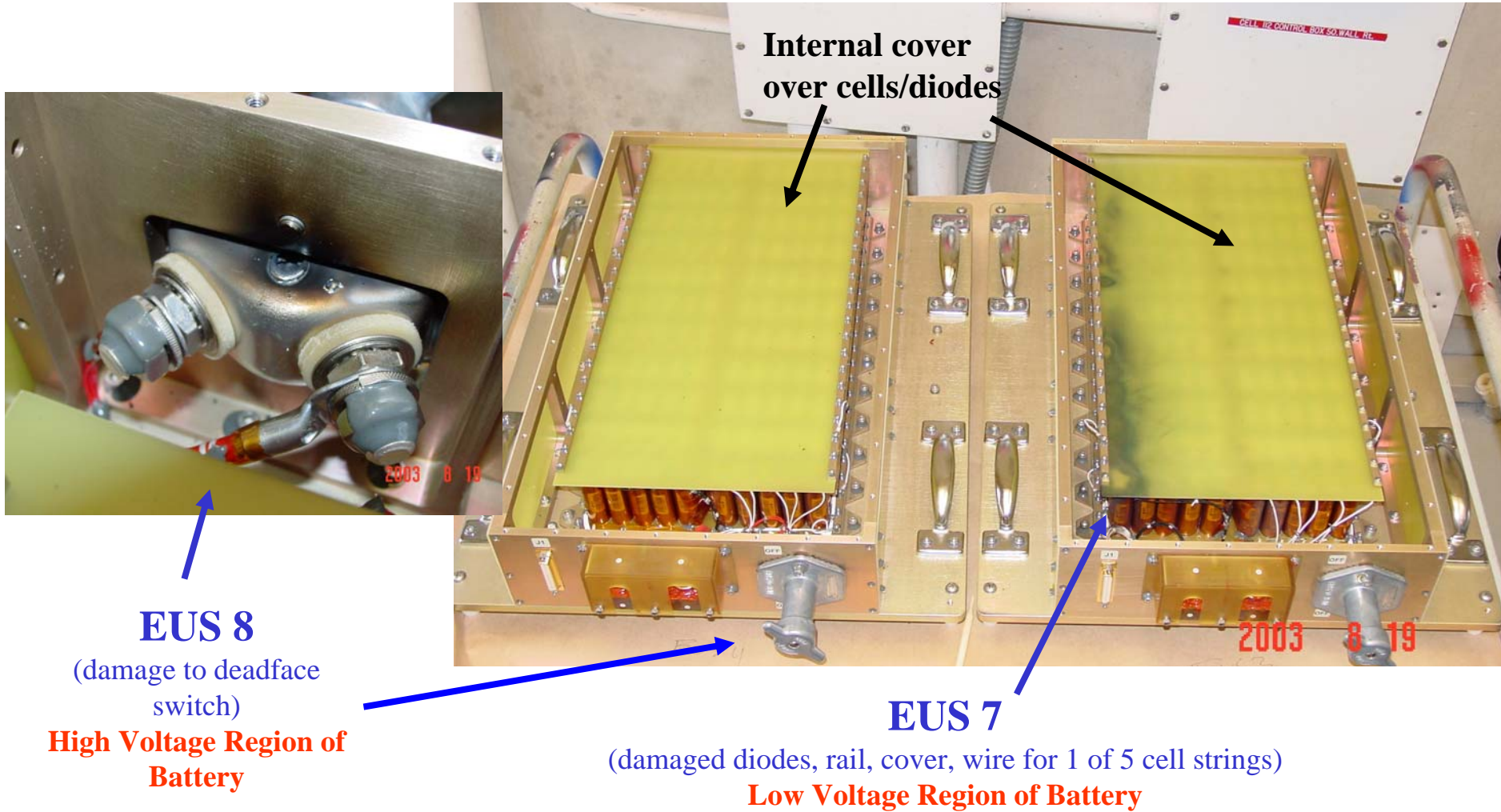
EUS 8

(module with deadface switch damage)



Note: This is normally a low voltage portion of the battery. Only because of a problem at the deadface switch, did sufficient voltage exist to cause discharge here.

Thermal Vac test showed corona failure.



Cell CIDs open under high voltage with no arcing



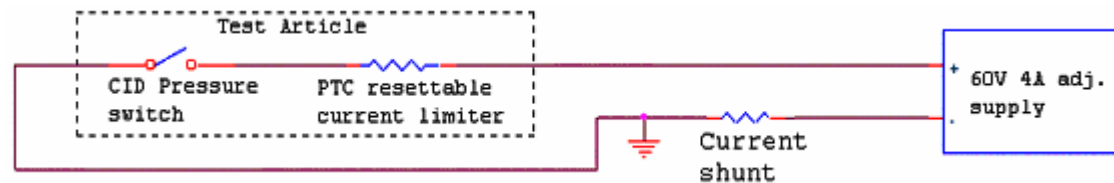
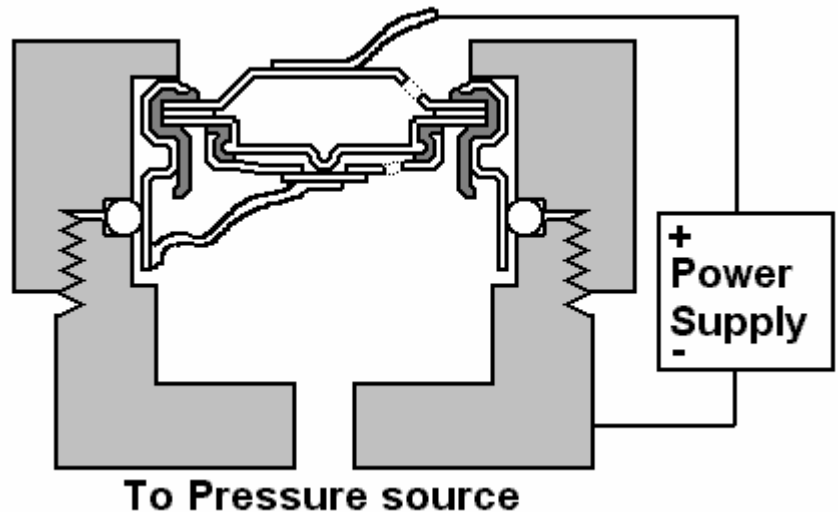
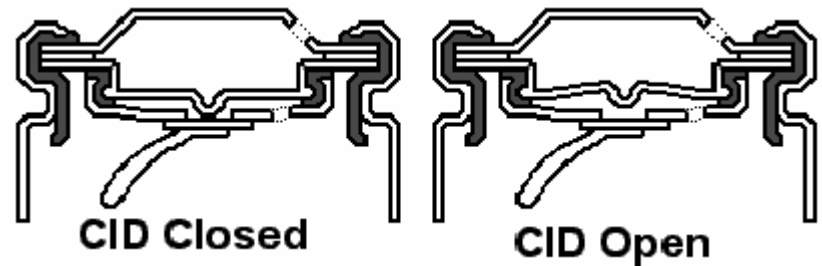
- 18650 cells have pressure activated switch (CID) that prevents overcharging.
- In high voltage batteries with diodes failed short, the cells in the shorted string will overcharge. When the CIDs open they may arc and burn a hole in the CID membrane.

Test setup:

- Electrochemical part of cell removed.
- CID pressurized with CO₂
- Pressure increased until CID opened.

Test results:

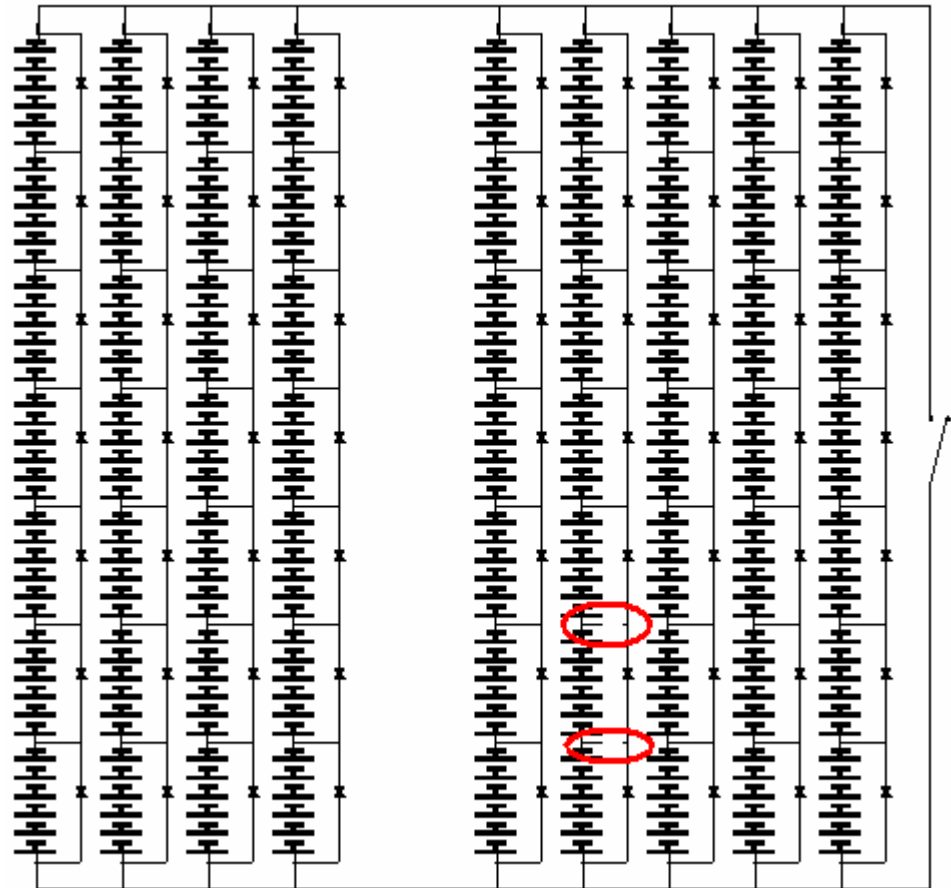
- CIDs opened at 218-242 psid.
- No arcing damage visible when opening up 4A 54V.



Collateral Damage Test with small cells:



- Test setup:
 - Two EUSBs in parallel
 - Hard short
 - Links to diodes removed
- Test sequence:
 - Hard short applied
 - PTCs fail (shorted)
 - Battery temperature rise
- Result:
 - No collateral damage
 - PTC failures did not cause further failures in neighboring cells.



Collateral Damage Test with small cells :



Slight blackening
and
discharge
visible at
vents of cells

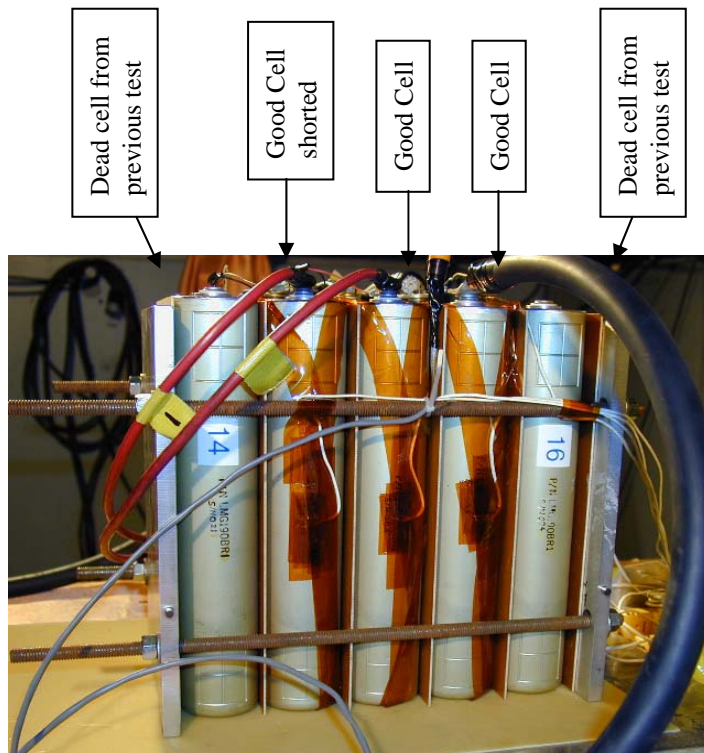


Collateral Damage Test with large cells

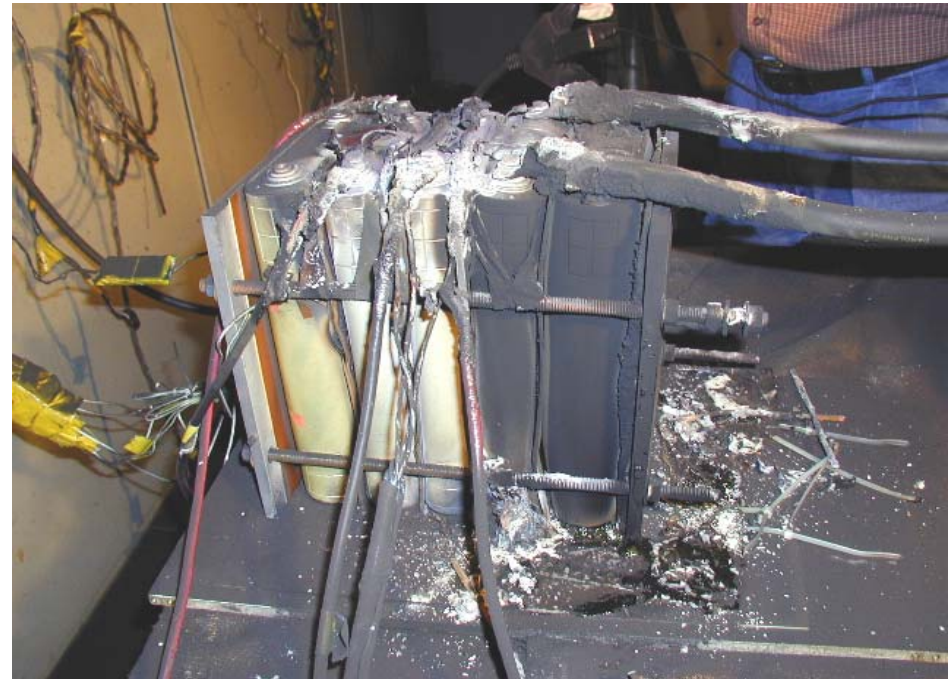


Objective - Determine consequence of a single cell critical failure on adjacent cells within a module

- External short (0.7 mohm) imposed on one cell (magnitude is known to cause cell venting) while a 65 amp load was placed on the other two good cells
- Results - Cell vented 42 seconds after application of short. Because of the heat generated, the 2 other good cells experience a heat-to-vent at 6 and 10 minutes.



Post Test



Conclusions



■ Conclusions

- Small cell battery approach is very feasible for EAPU
- Performance requirements are met with Sony HC cell
 - Battery size is driven by PTC during hot mission case
- Can recover and perform after a hard short
- Collateral damage test was a success

■ Future development

- Can alternate cell designs reduce the battery size?
- Two-fault tolerant diode scheme is needed
- Deadface switch with improved corona tolerance is needed